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The discussion in this article refers to gas welding of thin-walled parts of up to about 3 mm thickness.

Unalloyed steel of carbon content up to 0.3 percent, and chrome-molybdenum steel type 1452, had been successfully employed in welding since 1928 and 1930, respectively, by the German aircraft industry. In 1933, however, and the years following - during which there was a strong upturn in German aircraft production - a new type of failure, namely, welding cracks or fissures, made its appearance, assuming such alarming proportions as to affect seriously the structural safety of the aircraft. (The cracks considered in this article occur between the weld proper and the underlying steel, the surface of the weld appearing perfectly sound.) The cause of these cracks was entirely unknown. They occurred on steels of proven reliability, on new- as well as on old-type weld structures, and in the work of both long-experienced and inexperienced welders. As far as was known, there had been no change in the welding conditions. Yet some change must have occurred to give rise to this new weld-crack phenomenon that had previously been unknown. It was imperative to discover as quickly as possible what these changed conditions were, so as to eliminate the defect. Intensive investigations were at once undertaken covering not only welding technique but also design and materials.

Much information as to the effect of these manifold conditions on the crack susceptibility of welds was obtained from the investigations carried out by the Focke-Wulf Company in their tests of 1933-34 (reference 4). The important results obtained were that failure was not due to the welding technique, that weld stresses were a necessary condition for the occurrence of weld cracks, and that the magnitude of these stresses in the aircraft structure is not predictable, and hence hardly capable of being influenced; furthermore, that the welding stresses alone were

*"Über die Ursache der Schweissrissigkeit an Flugzeugbaustählen." Luftfahrtforschung, vol. 17, no. 4, April 20, 1940, pp. 97-105.

not a sufficient condition for the development of welding cracks but that, in addition, a certain property of the steel was a determining factor as to whether or not cracks would develop in a stressed weld.

An important aid in these investigations was the testing procedure developed by the author - a procedure by which the crack susceptibility of the steel could be assigned a numerical value. As a measure of the susceptibility, there was defined the percent of oxidized failure area of the weld. Meanwhile, in the very extended practical application of the new testing procedure, it was found that the percent length of the crack or the sum of the crack lengths was more convenient since in the case of small wall thicknesses, an estimate of the crack depth involves greater uncertainty than that of the crack length. This measure of weld-crack susceptibility was therefore generally adopted by order of the State Aircraft Ministry, February 4, 1936.

The main criterion for determining whether or not a steel can endure the weld deformations without developing cracks was found to be the carbon, sulphur, and phosphorus contents of the steel - an increase in the carbon content making necessary a corresponding decrease in the (P + S) content. Which of these two sets of impurities has the greater effect is as yet not clear. The degree of purity specified in DIN 1661 ((P + S) = 0.07 percent) which, in general, was sufficient for aircraft welded steels, was recognized to be insufficient for good welding properties of steels with higher carbon content. Cold or warm joining of the steel was found to have no effect on the crack tendency. Likewise, the hardness of the weld, i.e., increase in hardness in the overheated zone in the region of the weld seam, was the subject of the investigations and it was found that the weld hardness and the tendency to weld failure were not interrelated.

These results have been obtained essentially on unalloyed steels. They were, however, found to be fully confirmed for the chrome-molybdenum steel 1452. Figures 1 to 3 show the results of one series of the numerous tests conducted during the last five years by the Focke-Wulf Company. The C, P, S curves were obtained from 109 charge analyses of CrMo steel delivered in 1935-36 by three steel manufacturing firms and are based on a very large number of welds of the Focke-Wulf Company with steels of these compositions. All the available data during this

period were utilized to determine whether or not the steel employed was suitable for welding.

The C (P + S) curve of figure 1 shows, as was previously found with carbon steels, that there is a transition region which divides steels with welding-crack tendency from those without this tendency. The width of the transition region, about 0.005 percent (P + S), is surprisingly small, if account is taken of the fact that these are charge analyses and that appreciable analysis variations may occur in the charges themselves. The manganese content of the steels almost without exception was between 0.50 and 0.70 percent, so that the crack-reducing tendency of the rather high Mn content - a fact known from many tests (see below) - was not a disturbing factor. In similar manner the C-S diagram (fig. 2) and the C-P diagram (fig. 3) show the separation of the weldable steels from those with weld-failure tendency.

On the basis of the above results the Aviation Ministry, from January 1936 on, ordered a corresponding reduction in the S, P, and C content of the CrMo steel 1452 ($S \leqq 0.015$ percent and $P \leqq 0.020$ percent, $C =$ max 0.27 percent). From table I, it may be seen how the crack susceptibility of airplane structural steels was affected as a result. During the first half of 1936, the welding failures of the chrome-molybdenum steels became less and less frequent until they completely disappeared. Only now and then could welding cracks be observed in airplane welded structures, thus confirming the content specification.

Within the period considered, nothing essentially new appeared in the steel-production process except that some steel works went over to the electrical process and smaller charge weights - methods by which the uniformity and the degree of purity of the steel were improved. The degree of phosphorus and sulphur impurities before the occurrence of weld failure, was as follows:

$$P = (0.012 \text{ to } 0.024) \text{ percent}; \; S = (0.004 \text{ to } 0.010) \text{ percent}$$

The above facts provide a clear explanation of the principal cause of the weld-crack phenomenon in airplane construction. Although other conditions may have some effect on the crack tendency, they are of less importance, by far, than the composition of the steels. These other factors that may have some effect will be individually considered. First, the effect of various operating condi-

tions under which a sound or faulty weld may be reproduced will be shown, and then brief consideration will be given to the points of view according to which the crack tendency is explained by physical or chemical effects.

In recent years the phenomenon of weld failure and its causes have received intense investigation by many interested in this problem without, however, as the comprehensive literature shows (references 3 to 17), any clarification or agreement having been reached. A further contribution to this subject, therefore, will be made here.

TABLE I. Weld-Crack Susceptibility of Aircraft Structural Steels 1452 Determined by Focke-Wulf Co., 1936-7

	1936				1937			
	No. of specimens	No. of specimens E-welded	No. of specimens with welding cracks	Percent crack susceptibility	No. of specimens	No. of specimens E-welded	No. of specimens with welding cracks	Percent crack susceptibility
January	2750	616	66	10.7	5317	559	0	0
February	2785	867	105	12.2	2287	383	0	0
March	2662	1400	151	10.8	2868	669	0	0
April	3398	962	15	1.5	2139	796	0	0
May	6539	1351	32	2.3	843	270	0	0
June	5099	1303	7	.5	1202	353	0	0
July	6272	2747	100	3.6	1584	317	0	0
August	3450	1184	0	0	793	218	0	0
September	~5000	1259	0	0	2732	169	0	0
October	1573	1072	33	3.0	884	71	0	0
November	3046	889	0	0	357	18	0	0
December	3203	834	0	0	235	21	0	0

The point of view of welding technique is discussed with less and less frequency in the literature - an indication of the small importance attached to this factor as regards welding-crack susceptibility. It should be mentioned that the blame often put on the "less experienced" welder (references 5 and 6) for the development of cracks in welded airplane constructions, cannot be justified, provided, of course, that the rules for good welding technique are adhered to. No unique, essential effect of such factors as the mixture ratio of the welding gas (within the restricted limits occurring in practice), the flame size, the position of the burner, and the speed of the welding operation, could be established, in spite of repeated attempts to do so. Such an effect, if it existed, would so strongly depend on the highly variable conditions in aircraft construction, that it could not in general be predicted. Only in the case of individual parts which are to be produced in large numbers, can an optimum succession of weld operations on weld-sensitive material be empirically determined. Such a method will never satisfy the justified demands for safety and economy in aircraft construction. It may be mentioned that, with relatively small welding flame, as a result of smaller weld deformations, and with rightward or backward welding, a favorable effect may in some cases be observed on account of the after-annealing. The data, however, are not unique, so that this effect must be considered as doubtful and not conclusive.

Also the type of welding gas and its composition have been considered among the causes of weld cracking, in tests of the Coal and Iron Research Institute at Dortmund (reference 8). From a study of the available data gathered from various sources - the Focke-Wulf and Ernst Heinkel companies, the Fr. Krupp Works, Essen, and the State Materials Testing Institute, Berlin-Dahlem, the following results (presented in a brief report of the Thirteenth Acetylene Congress), were uniquely established:

The sulphur and phosphorus content of the welding gas has practically no effect on the tendency to weld cracking of alloyed and unalloyed aircraft structural steels. As high a degree of purity as possible of the gas, nevertheless, is recommended since, according to the investigation, the danger of weld failure decreases rather than increases with increasing purity of the gas. The effect is so small that it is not directly demonstrable but is surmised from the effect of such large impurities in H_2S and PH_3 as must purposely be added.

The question whether and to what extent the type of construction may possibly be taken as a cause of weld failure, rests on the following considerations:

1. To what extent can the airplane constructor avoid weld deformation and stresses?

2. Of what importance are the weld deformations for weld failures? (To be answered quantitatively, as far as possible.)

The first question has been considered with fruitful results in my first paper on weld cracks (reference 4). It was shown that the tensile deformations or stresses which arise at any point of the welded joint at right angles to the direction of the weld seam in the plane of the sheet may be composed of 1) a more-or-less-rigid fixing effect alone, as in the case with edge welding (indirect weld deformations) but that in addition 2) even with simple weld constructions - T-welds, for example - additional deformations may occur, so that to simulate these conditions in the weld, the two edges must be separated at the critical instant (indirect weld deformations). Since these stress conditions cannot as yet be determined - not only quantitatively but qualitatively - the first of the above two questions is to be answered in the negative.

In regard to the second question - whether and to what extent large tensile strains in the weld have an effect on the weld-crack development of various steels - the following test results may here be presented:

Four chrome-molybdenum steel sheets 1 mm thick, whose degrees of crack susceptibility were determined by 20 welds, as 0, 0.9, 7.4, and 13.1 percent, were further tested on the same apparatus - with the difference, however, that one of the two specimens to be joined was replaced by another of greater wall thickness, 3, 5, and 8 mm, and not subject to weld failure. In welding practice, such different wall thicknesses of pieces to be welded together are as far as possible, avoided. With these specimens, the weld strain at right angles to the seam, instead of being uniformly distributed over the two sheets, was borne mainly by the weaker sheet to an extent depending on the varied cross-sectional ratio. With wall-thickness ratio 1:3, the stretching was 1.5 times the normal; with 1:5 it was 1.67 times; and with 1:8 it was 1.78 times, if

the same total stretching is assumed for all wall-thickness ratios.

The welding-crack lengths referred to the seam length for the four test specimens, are plotted in figure 4 against the wall-thickness ratio. Each point is the mean value taken from ten welds. Whereas the good steel shows no trace of weld failure up to a wall-thickness ratio of 1:5, and only about 1 percent with eight times wall thickness, the other steels, with a slight weld-failure tendency with an increase in the weld deformation, show several times the weld-crack susceptibility than with normal welding. The second question is therefore to be answered as follows: Increase in the weld tensile deformations or stresses produces considerable increase in the crack tendency with steels that already have that tendency, but with steels that have no such tendency, these strains have no effect. With the latter steels, slight cracks occur only with very large weld deformations not normally to be expected.

It may be seen that in all cases where unforeseen weld stresses arise, the designer of weld constructions cannot be made responsible for the occurrence of weld cracks. He requires a steel which can balance these stresses without cracks. Too high welding stresses or too heavy weld constructions cannot be given as an essential cause of weld failure.

We have thus arrived at the viewpoint that the structural material employed for the weld is the factor essentially responsible for weld cracks in aircraft constructions.

With regard to the weld hardness, the formation of martensite in the overheated zone, the investigations of Bardenheuer and Bottenberg (reference 12) show that there is no connection between this property and the weld sensitivity. Elsewhere in the literature (references 10 and 13), it is stated that with increase in the hardening elements, C, Cr, Mo, and Mn, the tendency to crack development is increased. According to reliable experience in aircraft construction, the finding of Bardenheuer and Bottenberg is correct. As an example of this, it may be mentioned that the CrMoV steel 1456 - in spite of the high welding hardness of H_B (2.5/187.5/30) = 400-480 kg/mm^2 - in the following composition shows absolutely no crack tendency: 0.32 percent C, 2.46 percent Cr, 0.10 percent V, 0.69 per-

cent Mn, 0.013 percent P, and 0.009 percent S; Mo undetermined. This steel has been used for welding and subsequent heat treatment for certain airplane parts with good results. The content specification was seen to be valid also for this steel, as shown on the diagram of figure 5, obtained from 163 weld tests.

That a higher manganese content has a direct effect in decreasing weld-failure tendency, is an old fact gained from experience in aircraft construction (reference 16, discussion by Cornelius). Thus, several years ago the Ernst Heinkel Company proposed a chrome-molybdenum steel with increased manganese content that would relieve the analysis restrictions with regard to the sulphur content. Such steels were then investigated by the author: for example, 0.23 percent C, 0.92 percent Mn, 0.20 percent Si, 0.013 percent P, 0.038 percent S, 0.74 percent Cr, 0.35 percent Mo. Since it is a question of normally melted electric-furnace steel, the degree of crack susceptibility obtained of 0 percent with these C and S contents in all the tests, can only be explained by the increased Mn content. The same explanation holds for the widening of the weld-failure range in the C-S diagram obtained by O. Werner, with manganese reduction of melted steels (reference 16).

On the importance of the other components in the steel, Scherer, in his discussion in reference 13, on the test results obtained, says:

Chrome-molybdenum steel sheets were produced from 12-ton charges by the same metallurgical process but with different sulphur content. The welding-crack test thus made possible a reliable determination of the effect of sulphur. The results obtained were the following:

CrMo steel 1452	P percent	S percent	Weld-Crack susceptibility percent
C always 0.25 percent; other components held within very restricted limits	0.012	0.008	0
	.013	.021	1.4
	.011	.048	46

From the above results, it is concluded that the sulphur content within the usual limits has no effect on the weld-failure tendency. It is only when the sulphur content far exceeds the usual amount that the strength of the weld is affected (reference 13, discussion).

Taking account of the fact that an important difference with regard to suitability for welding purposes exists only between the first and the last two steels, and that before rules regulating the content were in effect, steels with sulphur content above 0.21 percent were produced in large amounts and led to weld failures (fig. 1), it is impossible to agree with this conclusion. The tests clearly prove, rather, that with the normal manufacturing process, increased sulphur content alone may be the cause of welding cracks. They even justify the conclusion that the increased sulphur content is not merely an indicator of some other steel property that leads to weld failure, but is itself the direct cause.

This conclusion is justified also by the following data of Cornelius (reference 15), which merit consideration:

	C percent	S percent	P percent	Weld crack susceptibility percent
CrMo steel 1452	0.23	0.005	0.02	0
Other components about the same	.26	.017	.011	.7
	.26	.029	.013	3
	.26	.033	.034	57
	.26	.043	.034	58
	.25	.048	.011	46

On the basis of their investigations, Bollenrath and Cornelius came to the conclusion (reference 9) that the weld-crack susceptibility in German aircraft manufacture has become a relatively rare phenomena for the following reasons:

1. Production of steel in the electric furnace and reduction in the size of the blocks in the various steel works.

2. Lowering of the carbon content to less than 0.28 percent.

3. Lowering of the sulphur content to a maximum of 0.015 percent.

Finally, the content regulation is also thoroughly confirmed by the results of O. Werner (reference 16) in a C-S diagram for a number of investigated steels.

There may also be pointed out the effect of very high H_2S content of the welding gas on the weld-failure tendency; and it may be briefly mentioned that the author, by a three-hour annealing process at 1000° in a gas giving off sulphur, was able to produce 100-percent-crack susceptibility on good steels - probably as a result of reaction diffusion, provided the steel was not alloyed with manganese.

The unfavorable effect of high phosphorus content is reported by various sources, as, for example, by Bardenheuer and Bottenberg (reference 12), and by Cornelius (reference 15). There is sufficient basis for the assumption, however (for example, references 12 and 16), that the sulphur content has a far more important effect than an equal quantity of phosphorus. This may with great probability also be concluded from the large number of observations given in figures 1 to 3, namely, from the width of the transition region in relation to the scatter regions of the S and P contents and, especially, from the number of steels within the scatter regions. In the C-S diagram (fig. 2), there are about 30 points within the scatter limits, while in the C-P diagram (fig. 3), there are 48 points.

No proof, as far as known, is anywhere given of any appreciable effect in increasing or decreasing the tendency to weld cracking, by the Si, Cr, Ni, Mo, and V content of the steel.

On the effect of the usual heat treatments, Bardenheuer and Bottenberg - on the basis of convincing tests - state (reference 12) that as far as weld failure is concerned, it is of no importance whether the material is welded in the annealed or in the hard-rolled state. The same holds for normal annealing and heat treatment. Reliable aircraft-construction experience confirms this result.

Summarizing, the following may therefore be said: The importance of the many investigations in the laboratory and in operation for explaining the cause of weld cracks from the engineering and physical points of view, is undeniable.

With the present methods of steel manufacture, the weld failure of aircraft steel parts is essentially due to increased S, C, and P content. Agreement between manufacturer and consumer with regard to this fact would be very advantageous, and the doubts that often arise as to the correctness of the permissible content are, according to the above results, entirely unjustified (fig. 1).

Recently, there have appeared investigations on the possible effects on the weld-crack susceptibility of a particular melting process and melting treatment of the steel. Bardenheuer and Bottenberg investigated the effect of various metallurgical melting processes on a number of chrome-molybdenum steels and, simultaneously, the effect of the steel components and impurities (reference 12). The first chrages were held at particularly low melting and casting temperatures, and each charge cast in several blocks - the first in blocks with increasing carbon content, the second in blocks with increasing phosphorus content, and a third in blocks with increasing sulphur content. Thus, the steels rolled into sheets, gave the following results (the average of the degree of weld-crack susceptibility in the annealed and the unannealed states, was always taken since there is no fundamental difference):

Charge 1, C content between 0.28 and 0.36 percent, crack susceptibility 0 to 13 percent.

Charge 2, P content between 0.013 and 0.048 percent, crack susceptibility 11 to 60 percent.

Charge 3, S content between 0.013 and 0.065 percent, crack susceptibility 0 to 60 percent.

In the same way, further charges and blocks were produced with the difference that the melting and casting temperatures were purposely made higher than usual, so that the charges "cooked" for a certain time. These overheated charges gave the following results:

Charge 8, P content between 0.018 and 0.102 percent, crack susceptibility 0 to 42 percent.

Charge 9, S content between 0.011 and 0.035 percent, crack susceptibility 0 to 1 percent.

Charge 10, P+S content between 0.026 and 0.075 percent, crack susceptibility 0 to 5 percent.

Charge 11, P+S content of 0.66 percent, crack susceptibility 0 to 3 percent.

No specimens were taken of steels with varying carbon content.

The above investigations likewise clearly showed an increase in the weld-crack tendency with increasing content in C, P, and S. From a comparison of the two groups of charges, it was concluded, however, that this effect was far less than that of the melting treatment. The most important condition for small weld sensitivity is given as a sufficiently longer cooking period of the steel (reference 12).

With regard to the above conclusion, it is to be observed that the steels produced from "uncooked" charges have, with three exceptions, carbon contents of 0.29-0.36 percent, while the "cooked" charges, except numbers 5, 11, and steel 13/1 (see below) are lower in C content (0.23-0.27). This difference, which makes the results from the two groups of charges not directly comparable, should not be overlooked in evaluating the effect of overheating during melting.

These relations are most clearly brought out with the aid of the C (P+S) diagrams of the steels (fig. 6). Since the uncooked steels (underlined values in fig. 6) are entirely in the region of the higher C (P+S) content, while the cooked steels, generally free from crack susceptibility, are in the region of low content, it is not certain to what extent the weld behavior of the two groups of charges is due to the difference in effect already proven of these contents or to the varied melting treatment. In any case, by comparison of the results (fig. 6) with the other results - for example, those of figure 1 - overheating during melting is seen to have an improving effect in the region of lower carbon content, assuming lower melting temperatures of these steels and the same method of sulphur determination. The latter is of importance insofar as in the usual solution process still largely employed at that time with molybdenum steel, the total sulphur content is not all taken into account. In the neighborhood of 0.3 percent carbon content, tests with the given composition can in nowise lead to a convincing conclusion since in both figures 6 and 1 at 0.3 percent carbon content, the limit of incipient weld cracking lies at 0.025 percent (P+S).

In regard to the individual charges, the following must be said: Charge 5 with increased C content (0.42 percent) has such a high degree of purity (P = 0.010 percent; S = 0.008 percent) that, according to the analysis rule, freedom from weld cracks is to be expected. Similarly, with steel 13/1 (C = 0.28 percent, P = 0.010 percent, S = 0.005 percent). The weld behavior (weld-crack susceptibility = 0) of steels 11/1 (C = 0.28 percent, P + S = 0.066 percent and 14/3 (C = 0.25 percent, P + S = 0.072 percent) cannot be explained on the basis of the analysis rule - to which statement it must be remarked that the freedom from weld failure of the latter steel could not be confirmed in a later test (the steel was kindly made available by the Kaiser-Wilh. Inst. f. Eisenforschung), and that steel 11/2, which entirely agreed in composition with the steel 11/1, was subject to weld failure.

On the basis of these points of view and particularly, from the fact that through suitable regulation with regard to the C, P, and S content alone, freedom from weld failure may be attained also with steels melted and cast at very low temperatures, whereas with certain contents of the above-mentioned ingredients - in spite of the special overheating treatment - the steels could not be made free from weld cracks (8/5 and 6, 9/1, 10/6 and 11/2), the following conclusion from the test results is to be drawn:

The tendency to weld failure on CrMo airplane structural parts is essentially ascribable to the composition, namely, the increased sulphur, carbon and phosphorus content. This tendency, as shown by the test results and practical experience, may be reduced to a certain extent by special metallurgical treatment due to the lowering of inclusions and separating out of crystals, but cannot be eliminated independent of the composition. Correct composition is of first importance for the avoidance of weld cracking.

As a cause of weld failure, there are taken into consideration local stresses which arise through perlite and martensite formations as a result of crystal separation and through the bursting effect of hydrogen, for which oxide and sulphide occlusions at the grain boundary are of importance. The treatment of charge 13 with hydrogen did not result in weld failures, but with increasing hydrogen treatment an otherwise sound sheet may be made subject to weld failure. The known fact that relatively soft steels with low carbon content are subject to weld failure for

sufficiently high phosphorus and sulphur content to the same extent as high carbon and alloyed steels, however, speaks against any important effect of the above factor. Furthermore, the phenomenon proved by Cornelius (reference 15), and by Bollenrath and Cornelius (reference 11), that with arc-atom welding - in spite of the fact that the welding process occurs in a hydrogen stream - the crack susceptibility of steel is considerably lower than with autogenous welding.

Of further interest are the investigations of Bardenheuer and Bottenberg on the crack-tendency reducing effect of nickel-alloyed welding rods (reference 14). Unfortunately, on account of the raw-material situation, these results are not of directly practical importance.

Further investigations on the application of overheating during melting and special deoxidation methods, are reported by Eilender and Pribyl (reference 13) - these investigations being concerned with the temperature at which the weld cracking arises. This temperature was judged by appearance to lie at 650° C, in contrast with various other figures in the literature, all of which lie higher. (See below.) Through annealing tests it is then found that no relation exists between weld-crack tendency and grain size. Further, it is said that the formation of the crack depends on the deformability of the material in the temperature range of about 650° C, at which the crack arises. On the basis of investigations, the decrease in the deformability due to crystallization at 600° to 700° is given as the cause of the tendency to weld cracking. This is confirmed by a 24-hour diffusion annealing at 1270°, by which a sheet with crack tendency became insensitive to welds, decarbonization at the edge having no essential effect.

Furthermore, by special melting processes, several test steels were produced which, in spite of higher carbon, phosphorus, and sulphur content, were shown to be practically free of weld cracks. This is ascribed to the elimination of crystal separation, due to the special melting process. It appears, nevertheless, problematical as to what extent the high manganese content (up to 2.2 percent) of most of the steels employed contributed to this effect. With other steels the unusually large difference in the two contents stands out (P:S up to 10:1 and above), and the analysis rule, on account of the different effect of phosphorus and sulphur, cannot be directly applied as for the

aircraft structural steels used in practice, for which such large differences in the same steel do not occur.

The fact that nothing stands in the way of the application of steels of far higher strength, as far as the tendency to weld failure is concerned, is proven from long experience in airplane construction (reference 4). The unfavorable effect of the weld hardness, however, makes necessary a subsequent heat treatment which is not always possible in practice.

Pointing out of the importance of crystal separation is useful for explanation of the often-observed scattering in the weld-crack susceptibility tests, and for the knowledge of the cause of weld failure in general. It is obvious that not only the average analysis but the microcomposition of the endangered points is necessary. Much is known about the origin and importance of crystal separation for the steel properties (references 1 and 2). The separation which occurs during solidification within the crystallite, in the case of sulphur mostly between the crystallites, depends on:

1) the absolute magnitude of the solidification interval. Within the composition limits of structural steels in the case of the Fe-S system, it is a multiple of the solidification intervals of the Fe-P and Fe-C systems.

2) the speed at which the cooling progresses, particularly during the solidification interval. Since the crack region of the weld runs through this temperature range (or a portion of it) very rapidly, this condition, to a large extent, determines crystal separation independent of the previous degree of crystallization (mixture in the case of sulphur).

3) the magnitude of the diffusibility of the components during the solidification interval and thereafter. In this connection, it is to be noted that sulphur, which is soluble in iron only in traces, has an unusually small diffusibility, but phosphorus, too, which is soluble in α-iron up to about 1.7 percent, also diffuses very slowly, so that the accumulation of the phosphorus during solidification, occurs particularly in the presence of carbon.

In agreement with these fundamental rules, known from structural theory, experience also shows that sulphur stands first place in its tendency to produce crystal sep-

aration, followed by phosphorus and carbon, and that the crystal separation of sulphur, phosphorus, and carbon in many cases, is very important for the composition of steel. Owing to the accumulation of phosphorus and sulphur, unavoidable to some extent, in some cases even the absolute contents of these components must be held down to as small amounts as possible. In other cases, the average analysis determines the microcomposition of the welding-crack region.

In view of the above considerations, the importance of the nonhomogeneity of steel for welding-crack susceptibility must not be overlooked. That the degree of crystal separation, however, as Eilender and Pribyl (reference 13) maintain, is of greater importance for the weld-crack phenomenon than the average composition, cannot be accepted in view of the success obtained on restricting the sulphur and phosphorus content of the steel. The conclusion: "These results show that it is incorrect to ascribe to the chemical composition an exaggerated importance in regard to welding-crack susceptibility and to give definite composition specifications for avoiding this phenomenon" (reference 13), cannot be supported in view of the facts described above. On the contrary, there is no doubt that the large success, through the elimination of German aircraft construction in cooperation with the Air Ministry, could not have been attained by the "special melting procedure," even if their proposal of 1938 had already been brought before them. It must be assumed rather that there are at least certain difficulties in putting their proposal into practice, since up to the present time no steel producer has made use of the possibility of eliminating or slackening the undesirable composition restrictions by reducing the crystal separation.

From other considerations, also, the conception that reduced deformability gives rise to the cracks at 650°, finds no confirmation. As far back as 1936, Bollenrath and Cornelius reported on heat-cracking experiments (reference 8) which were carried out at the Mining Institute at Aachen, with the result: "The finding that also steels Nos. 1 and 2, insensitive to welds, show minimum strain values at high temperatures, speaks against any fundamental significance of reduced strain capacity at high temperatures as a cause of the occurrence of weld fissure." The temperatures of reduced strain capacity were thought to lie between 800° and 1000°. It was just in the range of 500° to 800°, however, both for the crack-susceptible and the nonsusceptible steels, that increases from 20 to 60

percent in the strain values were measured (fig. 7) so that, according to these results, there can be no question of a change in the deformability of crack-susceptible steels at 600° to 700°.

Recently, also, O. Werner (reference 16) in tests on the same type of strongly crack-susceptible and nonsusceptible steels, could find no difference in the tensile strength and strain, hence no decreasing deformability of crack-susceptible steel up to 750°.

Even though with the elimination of this trouble, the principal object is attained, it is nevertheless of interest to know by what physical process these cracks arise. In the literature many explanations are given, such as the already mentioned decreasing deformability at 650°, as a result of crystal separation. There is also considered the possibility that local stress differences, through the simultaneous formation of ferrite, perlite, and martensite due to crystal separation, could produce microfissures which, through the weld stresses, widen into visible cracks (reference 12). Similar considerations underlie the supposition that the varying hysteresis ranges of the steels have a certain importance with regard to the crack susceptibility - a result which could not, however, be confirmed by the tests of O. Werner (reference 16). Bardenheuer and Bottenberg consider as possible causes of weld cracking, the fact that in welding the hydrogen diffuses atomically in the steel and separating out again molecularly at the grain boundaries, can produce high pressures and tensions in the steel (reference 12). In further development of this idea, O. Werner expresses the opinion that the bursting of the structure through water vapor or hydrogen sulphide formation with the combined action of the sulphur and oxygen content of the steel, leads primarily to fissure formation (reference 16).

For an essential physical explanation of the tendency to weld cracking, only such viewpoints can be considered, however, as take into account the effect of higher S, C, and P content on weld-crack tendency. This is true only for the last of the above-mentioned hypotheses.

Such an explanation is offered by the consideration that higher sulphur content, particularly with rough grain and crystal separation at the grain boundaries, forms a eutectic iron-iron sulphide in the heated zone near the weld seam shortly before the melting point of the steel,

which is fluid above 985° C and interrupts the cohesion of the steel sufficiently to make possible the crack formation by the weld stresses. The same is true above 1181° of the eutectic FeS-MnS. This tendency is shown by the established facts that weld-cracking susceptibility is immediately eliminated by restriction of the composition alone, that an increase in the sulphur content alone can cause an otherwise good steel to develop weld cracks, as also high H_2S content of the welding gas and annealing of the steel in an atmosphere giving off sulphur; furthermore, by the crack-reducing effect of increased content of manganese, whose great affinity for sulphur is chiefly responsible, as is known, for the effective elimination of the harmful effects of the sulphur. The favorable effect of an improved homogeneity of the steel also supports this view.

The objection that the steels with weld-cracking tendency show no "hot short" in being worked into sheet or tubes (reference 16, discussion by Cornelius), can perhaps be removed by the consideration that stresses in warm working are considerably different from those that occur in welding under tensile stresses and that by the pressures arising in warm working the microfissures, for these small sulphur quantities, can immediately again be welded, which is not possible under tensile stresses. In this connection, importance should be attached to the finding (reference 16, discussion by Cornelius) that a copper overlay of the welding rod may lead to weld cracks in the same manner undoubtedly as "hot-short" copper. The two last-named hypotheses must therefore be considered for the explanation of internal crack development.

Of great usefulness for the explanation of the physical causes would be the exact determination of the temperature at which the cracks develop; Bardenheuer and Bottenberg (reference 12), by attaching thin thermocouple wires 3 mm from the weld seam, have measured temperatures between 600° and 740°, which they assume to be somewhat too low. From these results, Cornelius concludes (reference 13, discussion) that the cracks arise at above 800° since they are first recognizable when they begin to open wide with further shrinking.

Tests of a similar kind which were carried out by the Focke-Wulf works may be mentioned here. In order to eliminate as far as possible the subjective effects in crack observation, the tests were carried out with five different observers. Moreover, good, and crack-susceptible, steels

were welded in irregular order without the observer's knowledge, so as to obtain a certain reliability in the crack observations. After a certain amount of practice in a room cut off from daylight, no error observations occurred. The crack is very clearly outlined to the eye adjusted to the darkness as a red line on the white-heated material. At this point the temperature was measured with a thermocouple at the instant indicated by the observer. The welding is then immediately interrupted in order to check the reading as far as possible. In this manner, temperatures between 770° and 1060° - on the average, 925° - were obtained by various observers. The greatest frequency lies around 1000°, figure 8. In this case, too, there is the probability that the crack was observed too late rather than too early, so that the temperature at which the crack develops lies at least at 1000° C.

SUMMARY

A brief description is given of the investigations and methods adopted to prevent welding cracks in German aircraft construction. It was proven that by restricting the sulphur, carbon, and phosphorus content, and by electric-furnace production of the steel, it was possible in a short time to remove this defect.

The various causes ascribed to welding-crack tendency in the literature are considered and the result arrived at is: that causes arising from welding technique are not responsible, nor the type of construction, and that the fundamental cause of weld-crack development lies in the composition of the material.

Weld hardness - i.e., martensite formation and hardness of the overheated zone - has no connection with the tendency to weld-crack development. Si, Cr, Mo, or V content has no appreciable effect, while increased manganese content tends to reduce the crack susceptibility.

All experience with aircraft construction, as also all investigations of the last eight years have given the one essential result, namely, that the tendency to develop weld cracks with unalloyed as well as with chrome-molybdenum and chrome-vanadium alloyed aircraft structural steels is caused principally by too high sulphur content in the

steel, which content with increasing carbon content must be correspondingly held within lower limits. High phosphorus content tends toward the same harmful effect. Nonuniform distribution of these components and crystal separation due to the accumulation of sulphur at the grain boundaries, can have an unfavorable effect. As high degree of purity and homogeneity of the steel as possible should therefore be aimed at. With the uniformity attained in present-day airplane structural parts, the average analysis of the C, P, S, and Mn content gives a good criterion for the welding behavior of a steel.

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Figures 1-3.- Analyses of 109 charges from 3 different steel works and corresponding welding tests of the Focke-Wulf Airplane Co.
○ Crack susceptibility= 0 %,
● Crack susceptibility > 0 %.

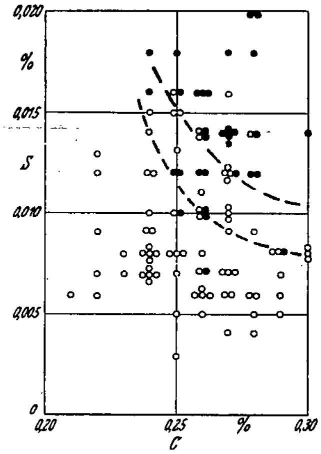


Figure 1. C-(P-S)-Diagram

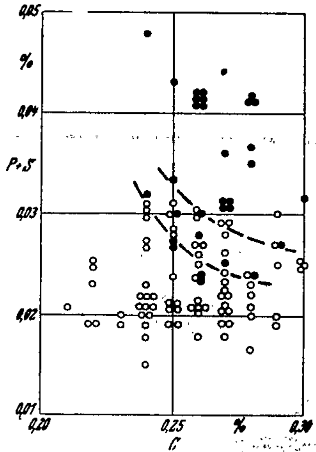


Figure 2. C-S-Diagram

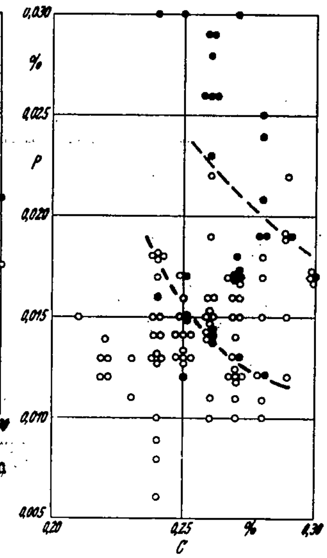


Figure 3. C-P-Diagram

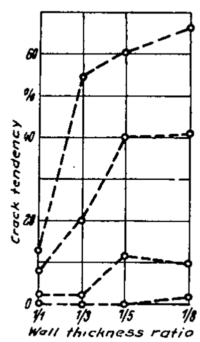


Figure 4.- Crack susceptibity of 4 different steels. Each point is a mean value from 10 weldings.

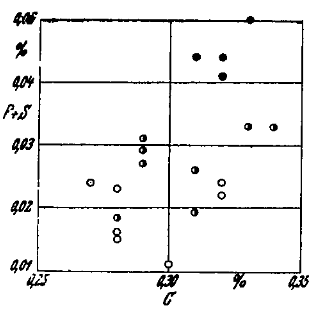


Figure 5.- Welding crack susceptibility of CrMoV steel 1456
○ 0 % susceptibility to weld cracking,
◑ 0-4 % , ● 5-25 %.

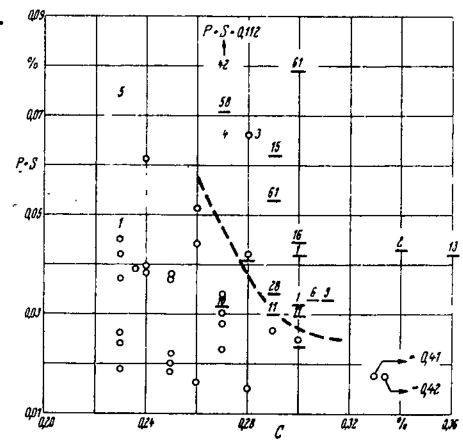
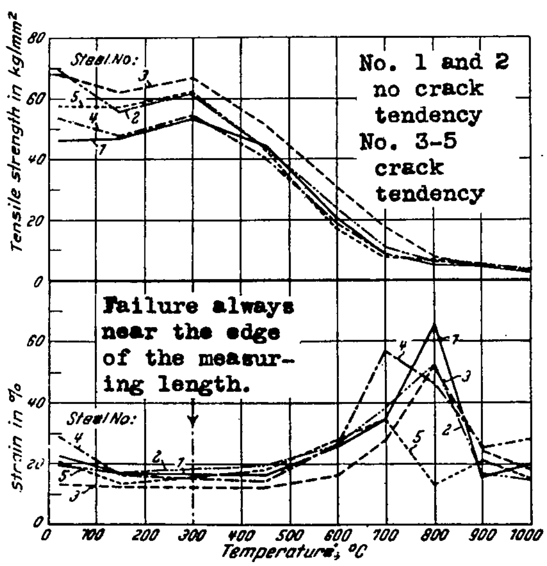


Figure 6.- Crack susceptibility in relation to melting procedure and C,P,S analysis of the steels investigated by the KWI. The figures give the degree of crack susceptibity. (○ denotes 0%). The values of the steels not overheated in melting are underlined.



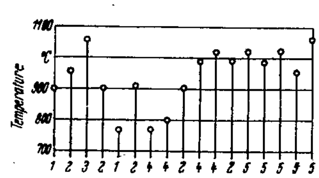


Figure 8.- Measured temperatures at which welding cracks arise.

Figure 7.- Tensile stress and strain of steel sheet with and without weld crack susceptibility as a function of the temperature after ½h annealing at 650° and cooling in air. (From Bollenrath and Cornelius).